NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3613

THE PROBLEM OF REDUCING THE SPEED OF A JET TRANSPORT IN FLIGHT

By Don D. Davis, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

The distance required to decelerate a high-speed jet transport from the normal operating speed to the design speed for maximum gust intensity (rough-air speed) has been calculated for the case of level flight with the engines idling. This distance was found to be much greater for a jet transport than for a typical piston-engine transport at the same altitude, and the distance was found to increase with altitude up to the altitude for maximum true airspeed. Because the increased distance for the jet transport was primarily a result of increased kinetic energy and, to a lesser extent, of lower drag coefficients, these results are believed to be qualitatively correct for high-speed transports in general. The exact distance for any particular airplane will, however, depend on the values chosen for the normal operating speed and for the rough-air speed (because these speeds control the kinetic energy that must be dissipated during deceleration) and also will depend on the airplane and engine characteristics.

The use of aerodynamic brakes, thrust reversal, or a climbing maneuver is shown to be effective in reducing the distance required to reach the rough-air speed, and therefore the use of such devices seems advisable. Even with the aid of such devices, however, the deceleration distance, at the altitude where it reaches a maximum, is likely to be considerably greater for jet transports than for present-day piston-engine transports.

INTRODUCTION

Whenever rough air is encountered in flight, the recommended practice is to reduce the speed of the airplane to the design speed for maximum gust intensity (see the definition of V_B in ref. 1 for commercial air transports). This speed, termed the "rough-air speed", is defined as that speed at which flight at the maximum normal-force coefficient would result in the same load factor as an encounter with a gust of specified velocity (40 feet per second in present regulations, ref. 1). The load factor determined from this definition is used in the design of the airplane, with the implicit assumption that the airplane will be flown at the rough-air speed V_{rough} whenever severe turbulence is encountered. In case the pilot has advance warning so that he can reduce the speed of the airplane to V_{rough} before it enters the turbulent air, this assumption is fulfilled. There are cases, however, when rough air is encountered without warning. In these cases, the distance that is required to reduce speed may have an important bearing on the loads imposed on the airframe, because, while the airplane is slowing down, the loads imposed by the rough air are higher than they would be if the airplane were flying at the speed V_{rough}. The influence of these additional loads is contained in the operational load experience gained from previous and present-day piston-engine airplanes. Designing a new airplane in accordance with this experience is satisfactory as long as the flight regime and the configuration are not radically different from those of previous airplanes.

In the case of turbine-powered transports, the speed and altitude will be quite different from the range covered by present experience and, in addition, significant reductions in the airplane drag coefficient will be made. The question naturally arises as to whether these changes will result in an increase in the loads during airplane deceleration in rough air. One way to determine whether a significant increase in load is to be expected is to compute the distance required to decelerate a high-speed jet transport to the rough-air speed and then to compare the result with the distance required to decelerate a typical piston-engine transport. Such comparisons are made in the present paper and, in addition, the effects of aerodynamic brakes and rate of climb on the deceleration of a hypothetical jet transport are considered.

An additional problem that has not been resolved is how accurately the pilot can maintain the rough-air speed after reaching it. This problem is not considered in the present paper. Also not considered is the question of how often either thunderstorms or clear-air turbulence are encountered without warning.

SYMBOLS

C_D	drag coefficient
ΔC_D	incremental drag coefficient due to aerodynamic brakes
C_L	lift coefficient
g	acceleration due to gravity, ft/sec^2

q	dynamic pressure, lb/sq ft
R/C	rate of climb, ft/min
V_C	cruising airspeed
V_{normal}	normal operating airspeed
V_{rough}	design airspeed for maximum gust intensity (called V_B in ref. 1)
W/S	wing loading, lb/sq ft

CALCULATIONS

The true airspeed as a function of the altitude is shown in figure 1 for a piston-engine transport and for a hypothetical jet transport. For both airplanes, the curves labeled V_{rough} correspond to constant indicated airspeed, 180 mph for the piston transport and 250 mph for the jet transport. The curve labeled V_{normal} for the piston transport corresponds to a constant indicated airspeed of 225 mph, which is the normal operating speed of a particular class of transports. In the case of the jet transport, the operating speed was estimated on the following basis. Because a high rate of climb is important to the economy of jet-transport operation, the design cruising speed V_C (see ref. 1) was chosen to be the speed for best rate of climb at sea level, 380 mph. The indicated speed for best rate of climb will normally decrease with altitude and, thus, the indicated speed in the climbing phase of the flight would be expected to decrease with altitude. On the other hand, a high-speed descent is economically desirable; thus, the descent is likely to be made at a constant indicated airspeed near the design cruising speed at sea level. As a result, a certain amount of flight at the speed V_C seems likely at all altitudes. The calculations for the jet transport are therefore based on this speed, and the resulting true-airspeed curve is shown as V_C in figure 1. The sudden change in the slope of this curve at an altitude of 30,000 feet is a result of the assumption that above this altitude the airplane will fly at a constant Mach number. Thus, the highest true airspeed is reached at 30,000 feet, and it is at this altitude also that the difference between V_C and V_{rough} is greatest.

The distance required to reduce the speed from V_{normal} to V_{rough} at an altitude of 13,000 feet has been computed for the piston-engine transport with an assumed wing loading of 57.5 lb/sq ft. Calculations were made for deceleration by reducing power to idling and also by combined power reduction and climb. Similar calculations were made to determine the distance required to reduce the speed from V_C to V_{rough} at 13,000 feet, as well as at the more critical altitude of 30,000 feet, for the jet transport with an assumed wing loading of 50 lb/sq ft. This loading is assumed to be representative of the descent weight of a jet transport. Calculations were also made for 30,000 feet with a wing loading of 75 lb/sq ft, which is representative of the climb weight. For the jet transport at 30,000 feet at the descent weight, additional calculations were made to determine the influence of aerodynamic brakes on the distance required to reduce the speed.

The method followed in all the calculations was to divide the deceleration into four intervals, during each of which the dynamic pressure was reduced by one-fourth of the difference between the dynamic pressure q at the initial speed and that at the rough-air speed. For the average value of q for each interval, the corresponding lift coefficient was computed, and the drag coefficient was read from the curves presented in figure 2. (The jet transport was assumed to be flying just below the Mach number for drag rise; therefore, the variation of C_L with C_D is not a function of Mach number, within the range of these calculations.) The drag was then computed, and from this drag the engine thrust for idling operation was subtracted in order to obtain the net airplane drag.

For the jet engine, the idling thrust is a function of both altitude and Mach number. For the conditions of this calculation, the range of variation for a typical engine was found to be from about 5 percent to 29 percent of the available thrust at the altitude considered. Because of this wide variation, an average thrust value was calculated for each interval of the speed-reducing maneuver. For the piston transport, it was assumed that the initial condition represented flight at 60 percent power, and the engines were assumed to idle at 20 percent power.

After the drag computation was made, the average rate of energy loss due to drag was determined for each interval. To this value was added the rate of kinetic-energy loss due to climb or drag brakes, if any, in order to determine the total average rate of energy loss for the interval. From this sum and the total kinetic energy to be lost during the interval, the time required for the interval was computed, and, from the time and average speed, the distance covered was determined. The total distance was obtained by summing the distances for the four intervals.

The climb calculations were made for a constant rate of climb throughout the maneuver; thus, the airplane was assumed to be in the climb at the initial velocity before the speed was reduced. Because the higher rates of climb considered are greater than the maximum possible steady rate of climb for the airplane, a pull-up maneuver is required to reach the assumed rate of climb. This maneuver may increase the distance required to reduce speed, and the increase will be a function of the severity of the pull-up.

The drag-brake calculations were made for a constant incremental drag coefficient ΔC_D due to the brakes and for level flight of the airplane. By combining drag and climb (or descent) energies, any particular combination of brakes and climb (or descent) could be analyzed, but such combinations have not been included in this analysis because the trends could be determined from the separate drag and climb calculations.

In addition to the distance required to reduce the speed of the airplane, certain other quantities of interest were determined. For the climb case, the total altitude gained in the maneuver has been calculated. For the case of aerodynamic braking, the initial deceleration has been determined by dividing the total drag at the time the brakes are first extended by the airplane weight. The ratio of the initial brake drag to the thrust required for level flight has also been calculated in order to convey some idea of the magnitude of the drag load on the brakes. In addition, the steady-state rate of descent with idling power at the rough-air speed has been calculated as a function of the incremental drag coefficient due to aerodynamic brakes.

RESULTS AND DISCUSSION

Level-Flight Deceleration

The results given in figure 3 show that the distance required to reach the rough-air speed in level flight (zero rate of climb) with engines idling is 3.7 miles for the piston-engine transport (W/S = 57.5 lb/sq ft) and 14.5 miles for the jet transport (W/S = 50 lb/sq ft) at an altitude of 13,000 feet. The problem of reducing the speed of a transport airplane obviously has changed considerably with the advent of the high-speed jet transport. This change is primarily a result of the increase in the kinetic energy that must be dissipated in order to reduce the speed, but the lower drag of the jet airplane is also an important factor. For the jet transport, the kinetic energy increases with altitude and reaches a maximum at 30,000 feet, as is apparent from the true-airspeed curves in figure 1. This increase in kinetic energy has a powerful effect on the distance required to decelerate to the rough-air speed in level flight. The distance increases from 14.5 miles at 13,000 feet to 36.2 miles at 30,000 feet (fig. 3). For any specific airplane, the altitude at which the deceleration distance reaches a maximum will depend on the true-airspeed—altitude relationship chosen for the operation of that airplane. The altitude at which the gust loads are most critical will depend on both this relationship and the variation of design gust velocity with altitude.

From the preceding results, the need is apparent for a method of decelerating the jet airplane that is much more effective than simply closing the throttle. Two possible methods are climbing and the use of drag brakes.

Climbing Deceleration

Figure 3 shows the distance required to decelerate to the rough-air speed as a function of the rate of climb for the piston-engine and jet transports. These results show that if the airplane is climbing when rough air is encountered, the deceleration distance is significantly less than in the case of level flight. The wide difference between the two types of transports is apparent in the figure; also apparent is the important effect of altitude on the deceleration distance for the jet transport. Because of this altitude effect, it will be important to include in flight tests of deceleration the altitude at which the maximum true airspeed is reached.

The effect of an increase in weight on the deceleration distance is shown in figure 4 where wing loadings of 75 and 50 lb/sq ft are assumed to be representative of the climb and descent weights, respectively. In level flight, the distance required is increased by about 3 miles because of the increased weight of the airplane.

The factors that control the deceleration in level flight are the weight of the airplane, the drag, and the thrust. In this particular case (fig. 4), these three factors interacted in a manner such that the change in weight had a relatively small effect on the distance required to reach the rough-air speed. If the airplane were flying in a lower range of lift coefficient where the drag becomes nearly independent of the weight, as would be the case for considerably lighter weight or lower altitude, then the deceleration distance would increase approximately in proportion with an increase in weight. With increasing rate of climb, the difference in weight has even less effect on the distance in the present example, because the part of the total rate of decrease of kinetic energy per pound of weight that is due to climbing becomes a larger factor in determining the deceleration.

Figures 5 to 8 are plots of the true airspeed against distance traveled for various rates of climb for the piston-engine and jet transports with engines idling. Figures 5 and 6 are for an altitude of 13,000 feet and figures 7 and 8 are for an altitude of 30,000 feet. By observing the reduction in true airspeed in a distance equal to the width of a thunderstorm or the length of a patch of clear-air turbulence, some idea can be formed of the effectiveness of attempting to reduce the airplane speed as a means of reducing the gust loads. (Fig. 84 of ref. 2 shows that profiles of thunderstorms are about 4 to 9 miles wide and fig. 3 of ref. 3 shows that most nonthunderstorm turbulent areas are less than 20 miles in length.) If a typical turbulence profile is assumed, the information in figures 5 to 8 can also be used to calculate the loads imposed on the airplane for a particular deceleration technique. These loads can be compared with the results of similar calculations for flight through the same turbulence at the initial speed and at the rough-air speed to obtain a quantitative estimate of the effect of the deceleration on the loads imposed on the airplane.

Inasmuch as the deceleration distance has been found to decrease rapidly with increasing rate of climb, it is obvious that a descending airplane can be decelerated by closing the throttle, if it is not already closed, and executing a low-g pull-up to place the airplane in a power-off climb, if the resulting departure from the original flight plan is permissible. The distance required for such a maneuver would be of the same order as is shown in figures 3 and 4 for the same rate of climb, although it would exceed this distance somewhat as a result of the time needed to maneuver to the desired rate of climb. For example, when the deceleration is initiated, if the airplane is descending at 3,000 feet per minute at V_C with engines idling and a rather gentle pull-up (1.2g) is excuted to bring the airplane to a rate of climb of 4,000 feet per minute, calculations show that the distance required to decelerate is about $10\frac{1}{2}$ miles; whereas, if the airplane is climbing at 4,000 feet per minute at the time the throttle is closed, a distance of 9 miles is required. The time required for deceleration in $10\frac{1}{2}$ miles is about 76 seconds.

Although climbing is effective in reducing the deceleration distance, there are some penalties that accompany this technique when it is used during the airplane descent. The altitude gained in the climb must be lost again, and the time required to do so delays the flight and results in slightly increased fuel consumption. The altitude gained is plotted in figure 9 as a function of the distance required to reduce speed. The case of the piston-engine transport is included for comparison purposes. The time that is required to lose this excess altitude depends on the rate of descent. The rate of descent at the rough-air speed is considerably less than at the cruise speed; therefore, unless some type of drag device is used to increase the rate of descent after the climb, the jet airplane will arrive over the destination at a high altitude.

In order to obtain some idea of the drag requirements for steady descent at the rough-air speed, the rate of descent has been calculated for several values of the incremental drag coefficient due to the brakes, with engines idling. The results are plotted in figure 10, which shows the rate of descent as a function of ΔC_D for the jet transport at 30,000 feet at the descent weight. For a rate of descent of 2,000 feet per minute, a value of ΔC_D of 0.014 is required; whereas, for a rate of descent of 4,000 feet per minute, a value of ΔC_D of 0.033 is required.

Brake Deceleration

Inasmuch as the preceding discussion has shown brakes to be useful for the rough-air descent, it is of interest to consider the effectiveness of brakes as a device for reducing the speed of the airplane. The effect of drag brakes on the distance required to decelerate the jet transport from the initial speed to the rough-air speed in level flight at 30,000 feet at the descent weight with engines idling is shown in figure 11. This figure shows that brakes with a value of ΔC_D of the order of magnitude required for the rough-air steady descent (0.01 to 0.03) are very effective in slowing down the airplane in level flight. The effectiveness of the brakes in reducing the aerodynamic loads can be estimated with the assistance of figure 12 in which the true airspeed is plotted as a function of the distance flown, for a level flight deceleration at several values of ΔC_D.

In case of an inadvertent encounter with rough air, brake extension must be started within a matter of seconds to be effective, because the airplane is traveling at nearly 10 miles per minute. Consequently, in such a case it will not be possible to give much advance warning to the passengers. Thus if, in a certain altitude range, a high rate of deceleration is required to reach the rough-air speed in an acceptable distance, it might be desirable to have the passengers seated with safety belts fastened when flying in this altitude range.

The magnitude of the initial deceleration resulting from the use of brakes and reduction of power for speed reduction in level flight is shown as a function of the distance required in figure 13. When ΔC_D is equal to 0.014 (the value found to be sufficient for steady descent at 2,000 feet per minute), the distance in level flight is 12.1 miles and the initial deceleration is about 0.15g. When ΔC_D is equal to 0.033 (the value required for steady descent at 4,000 feet per minute at the rough-air speed), the required distance is only 6.4 miles but the initial deceleration is 0.27g.

Another factor regarding the use of brakes that is important in the design of the airplane is the size and weight of the brake mechanism itself. In order to get some idea of the forces involved, the ratio of the initial brake drag to the thrust required for level flight at the speed V_C has been computed. This ratio is plotted in figure 14 as a function of the distance required for the deceleration in level flight at 30,000 feet with engines idling at the descent weight. For the 12.1-mile distance discussed in the previous paragraph, the drag is about 1.1 times the engine thrust. For the 6.4-mile case, the drag is about 2.5 times the engine thrust. Obviously, these are large forces and the structure that withstands them will be heavy. The weight penalty might be reduced if the brake were a dual-purpose device - that is, if the braking could be obtained by modifying some other device that is necessary to the airplane, such as wing lateral-control spoilers or flaps or the landing gear.

The results shown in figures 11 to 14 have been for deceleration in level flight. If the airplane is descending when rough air is encountered and if the pilot desires to continue the descent while slowing down, the deceleration maneuver is more complicated. In practice, it would probably require an initial increment of brake extension, governed by the allowable longitudinal deceleration, followed by a further increment of brake extension when the dynamic pressure had been sufficiently reduced as a result of the reduced speed. Finally, after reaching the rough-air speed, the brakes would be partially retracted to the position for the selected rate of descent. This, incidentally, is one of the striking differences between flying the jet and the piston-engine transports. With the conventional transports, the pilot controls the rate of descent with the throttle, but with the jet transport, these calculations indicate that the rate of descent at the rough-air speed will be controlled with an aerodynamic brake.

Although the preceding discussion has been concerned with the use of brakes to obtain drag, drag can also be obtained by reversing the engine thrust. With a reverse thrust of 50 percent of rated thrust, the deceleration to the rough-air speed in level flight would take about 13 miles at 30,000 feet at the descent weight.

CONCLUDING REMARKS

The distance required to decelerate a high-speed jet transport from the normal operating speed to the design speed for maximum gust intensity (rough-air speed) has been calculated for the case of level flight with the engines idling. This distance was found to be much greater for a jet transport than for a typical piston-engine transport at the same altitude, and the distance was found to increase with altitude up to the altitude for maximum true airspeed. Because the increased distance for the jet transport was primarily a result of increased kinetic energy and, to a lesser extent, of lower drag coefficients, these results are believed to be qualitatively correct for high-speed transports in general. The exact distance for any particular airplane will, however, depend on the values chosen for the normal operating speed and for the rough-air speed (because these speeds control the kinetic energy that must be dissipated during deceleration) and also will depend on the airplane and engine characteristics.

The use of aerodynamic brakes, thrust reversal, or a climbing maneuver is shown to be effective in reducing the distance required to reach the rough-air speed, and therefore the use of such devices seems advisable. Even with the aid of such devices, however, the deceleration distance, at the altitude where it reaches a maximum, is likely to be considerably greater for jet transports than for present-day piston-engine transports.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 7, 1955.

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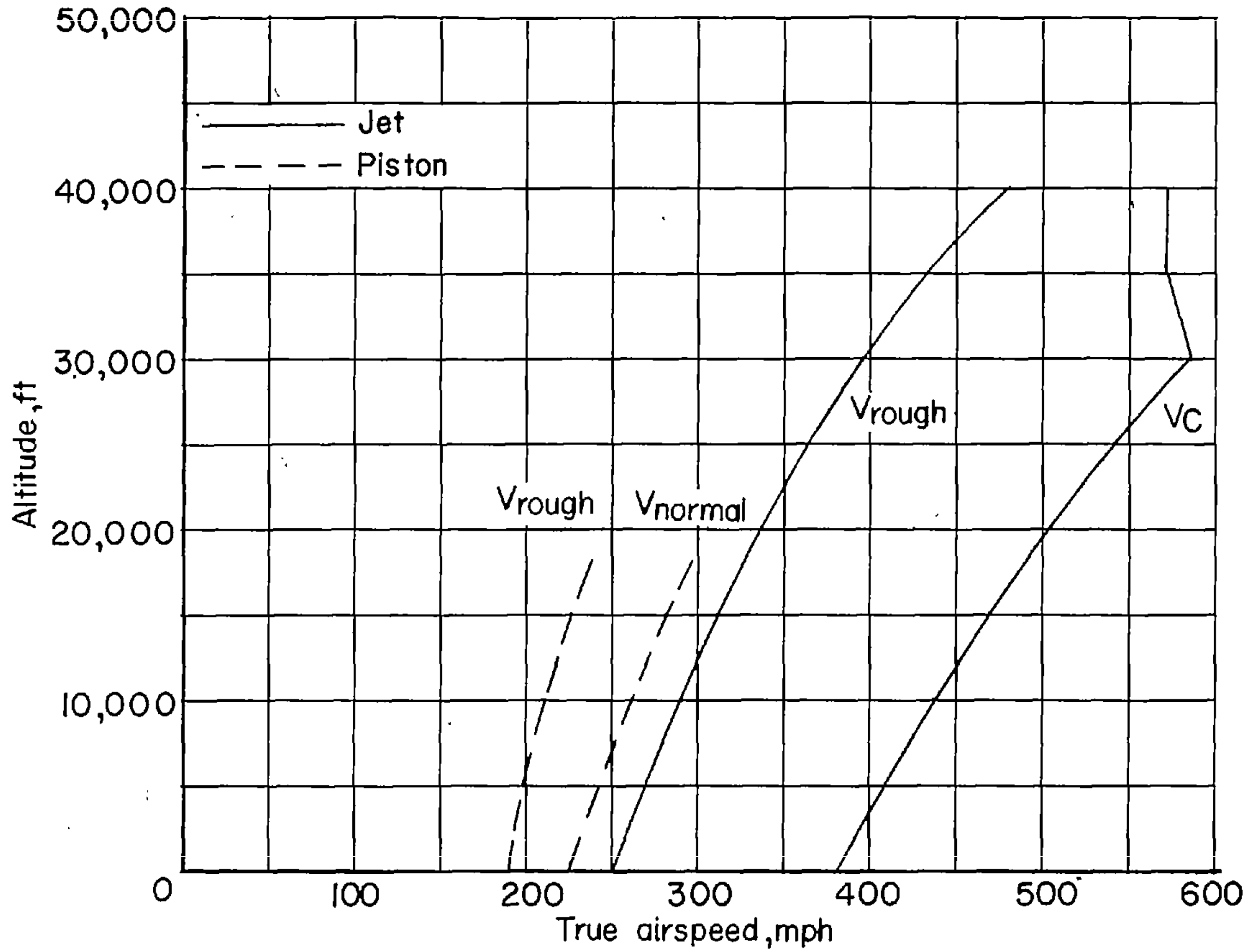

Figure 1.- Variation of true airspeed with altitude for a piston-engine transport and for a hypothetical jet transport.

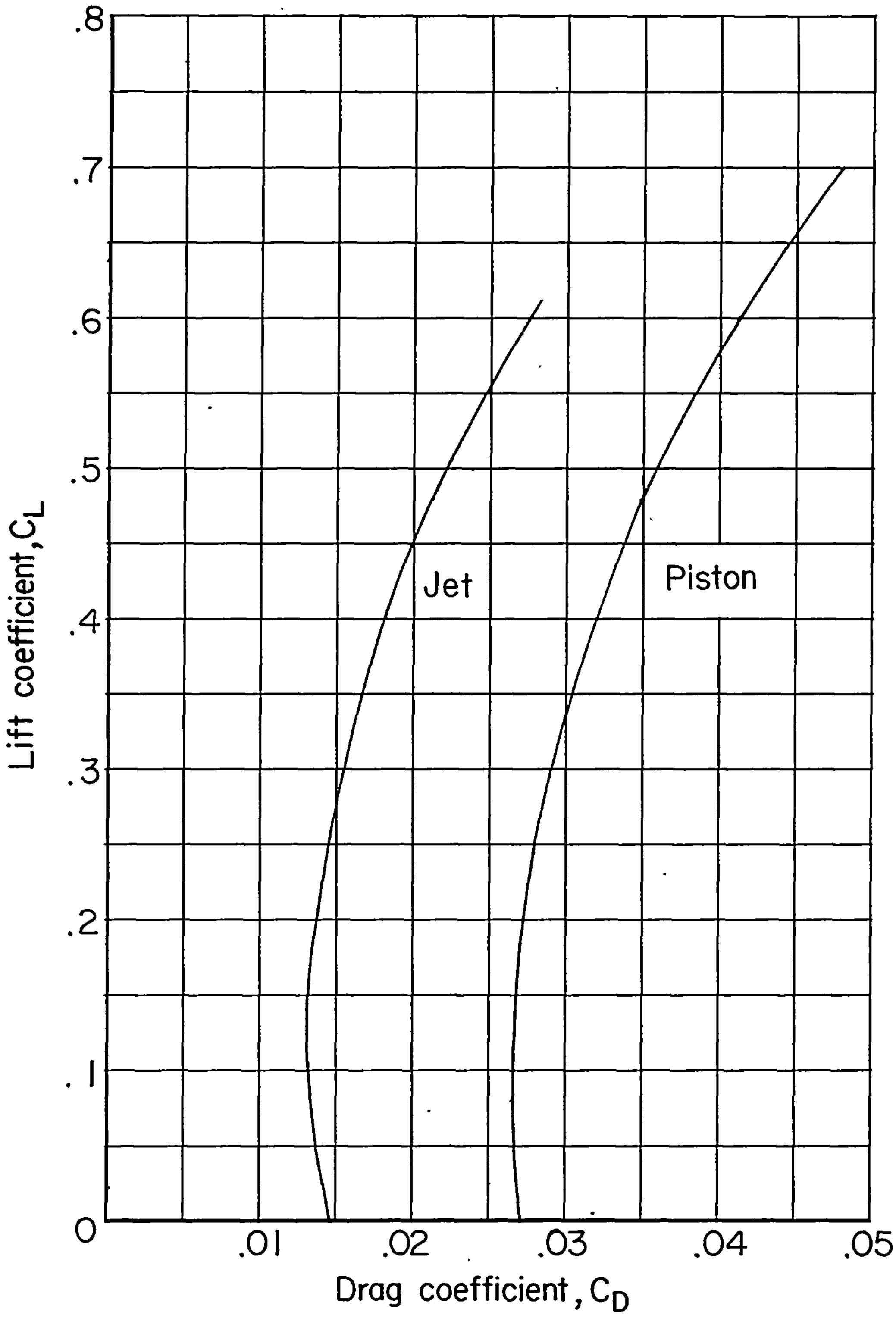

Figure 2.- Assumed drag characteristics of transport airplanes.

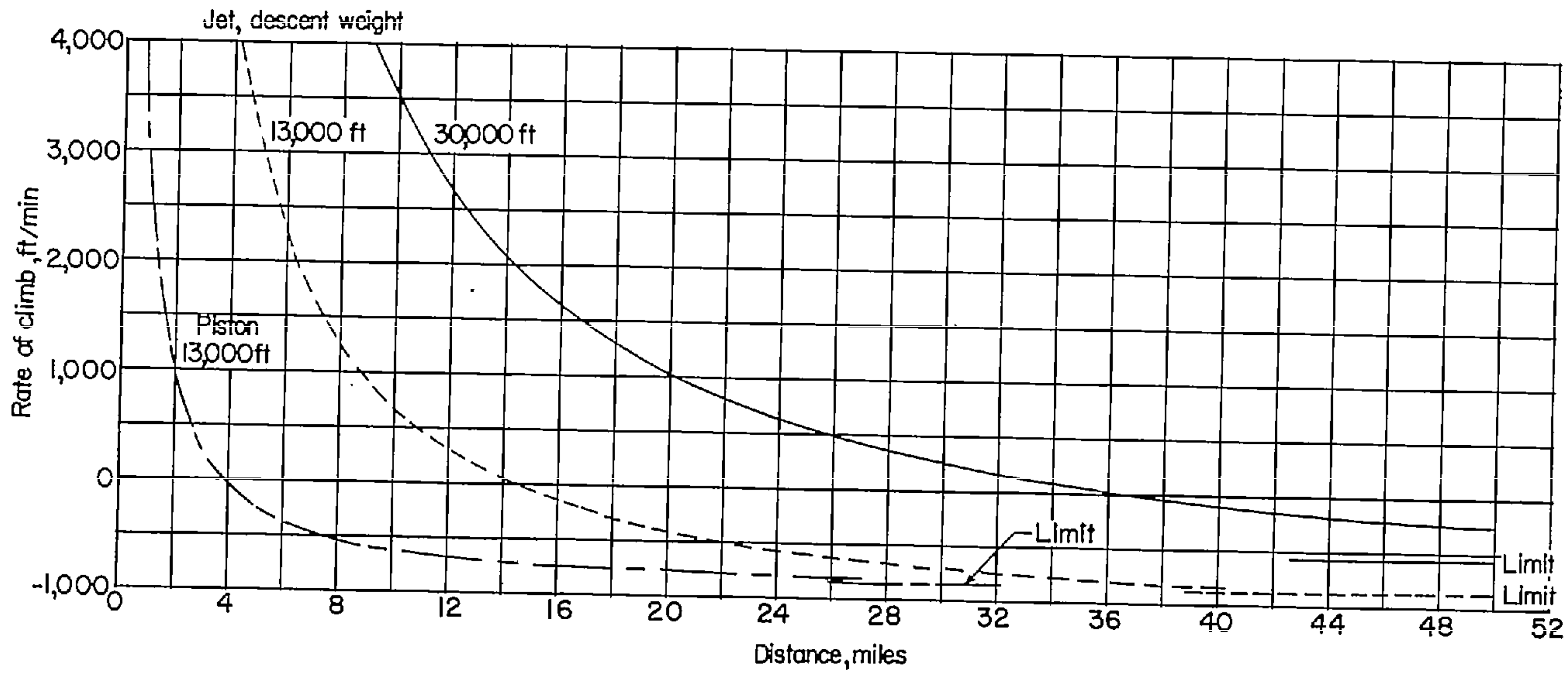

Figure 3.- Effect of rate of climb on deceleration distance for jet and piston transports. Engines idling; no brakes.

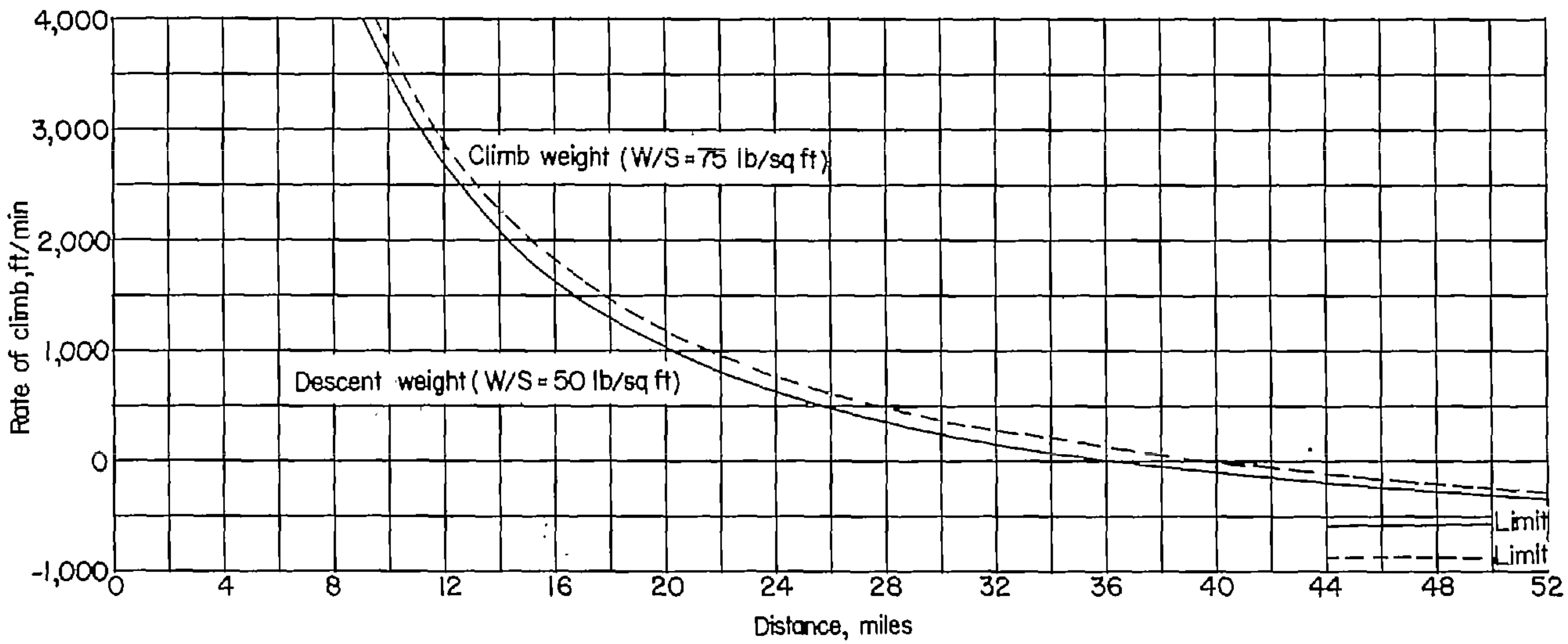

Figure 4.- Effect of weight on deceleration distance for jet transport. Engines idling; no brakes; altitude, 30,000 feet.

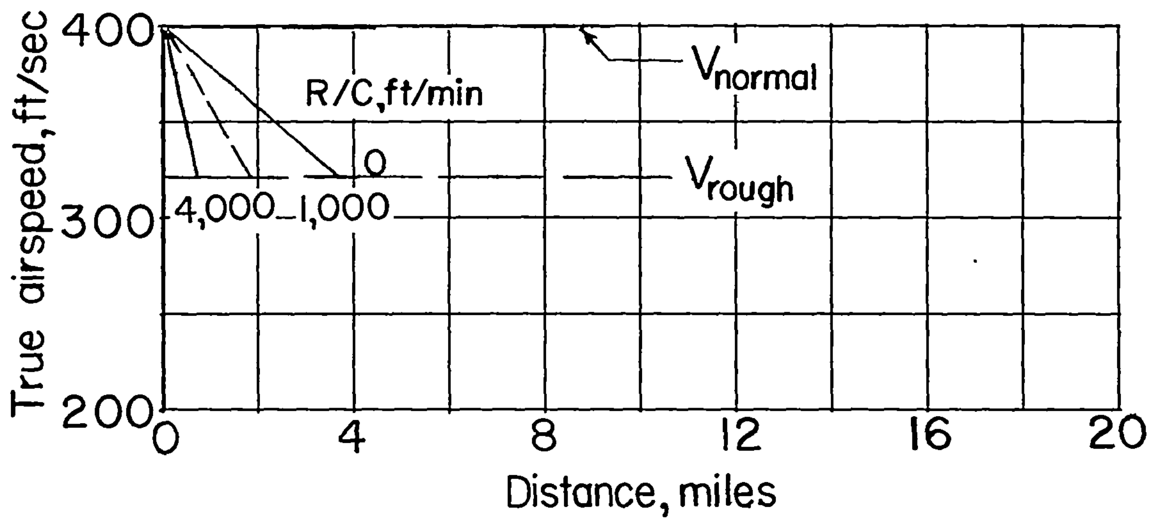

Figure 5.- Variation of true airspeed with distance for various rates of climb. Piston-engine transport; altitude, 13,000 feet; engines idling.

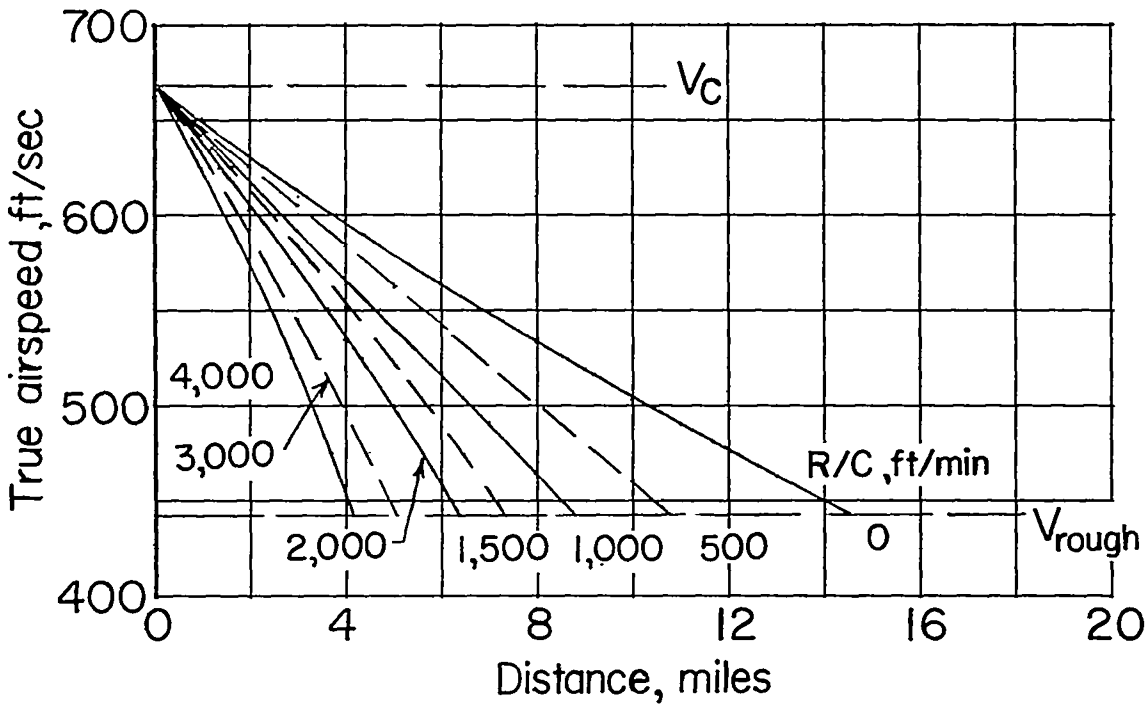

Figure 6.- Variation of true airspeed with distance for various rates of climb. Jet transport; descent weight; altitude, 13,000 feet; engines idling.

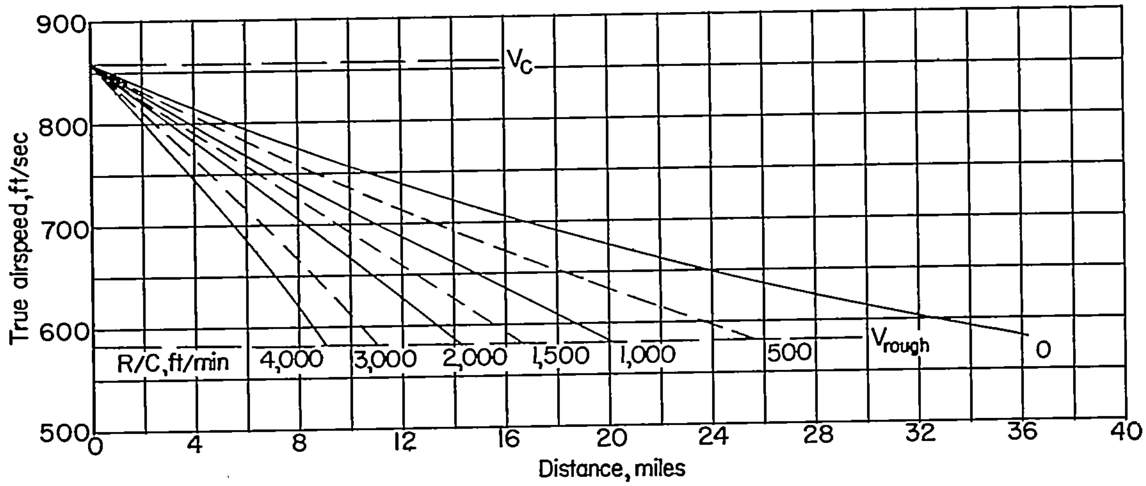

Figure 7.- Variation of true airspeed with distance for various rates of climb. Jet transport; descent weight; altitude, 30,000 feet; engines idling.

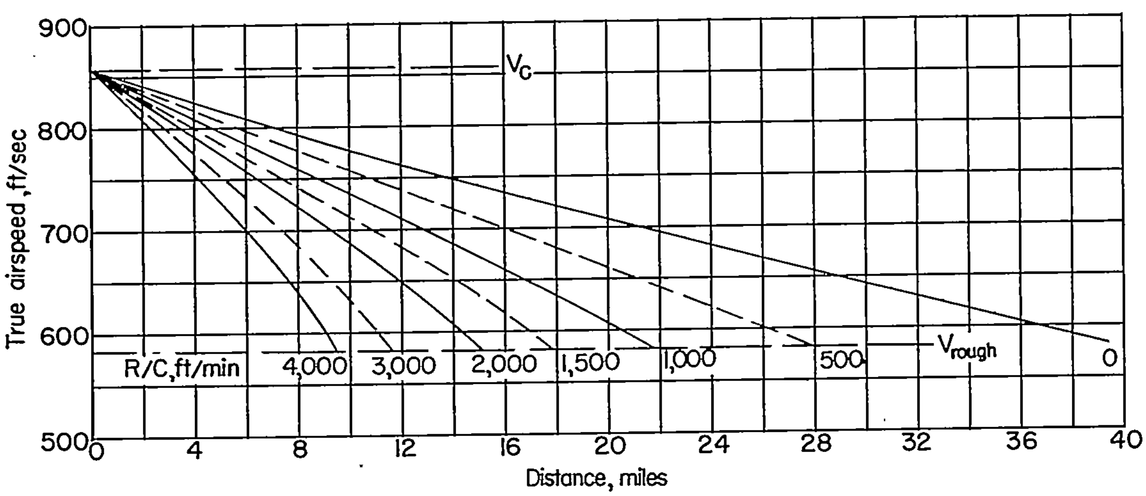

Figure 8.- Variation of true airspeed with distance for various rates of climb. Jet transport; climb weight; altitude, 30,000 feet; engines idling.

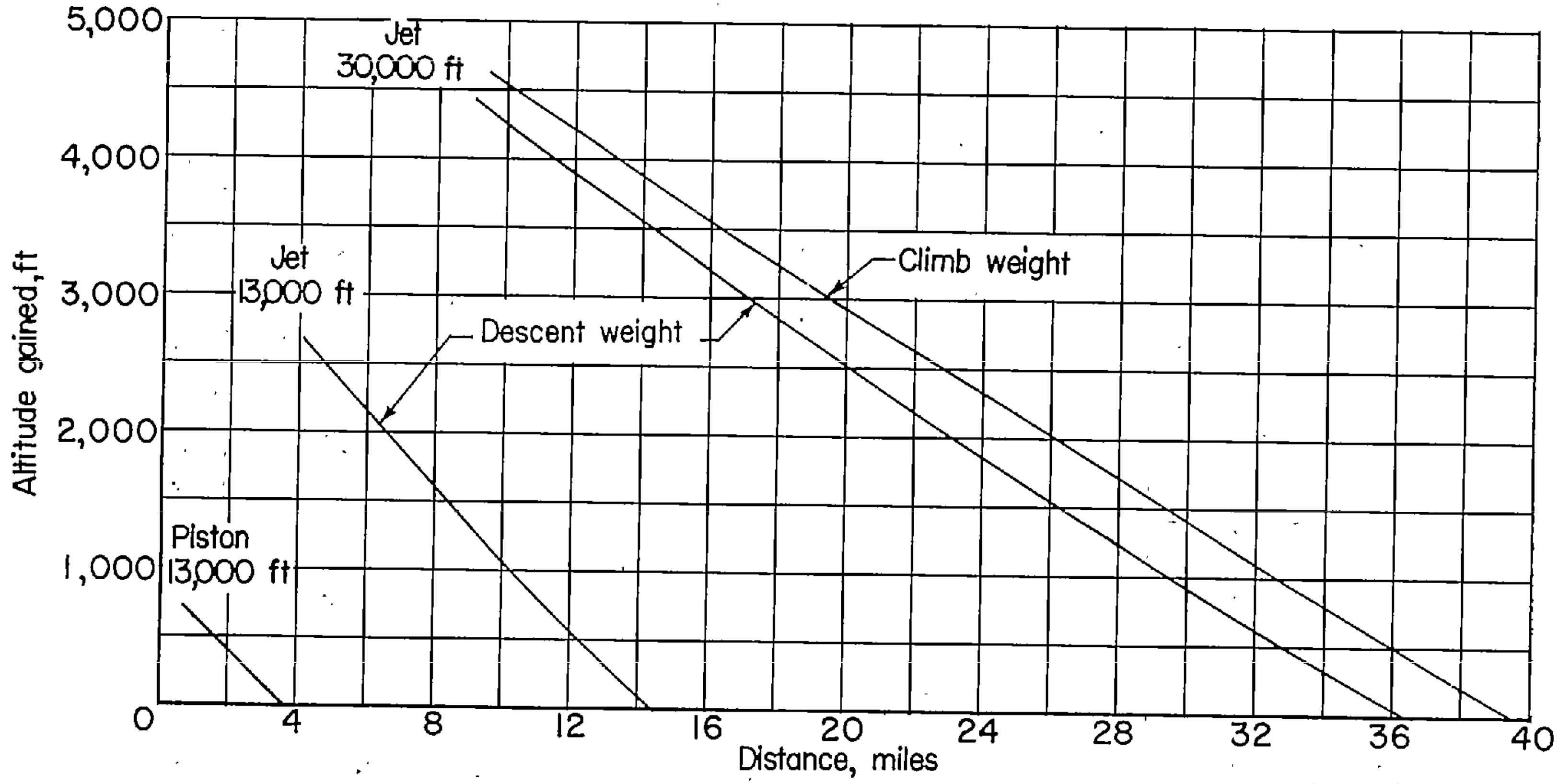

Figure 9.- Altitude gained in climbing deceleration as a function of distance required to reduce speed.

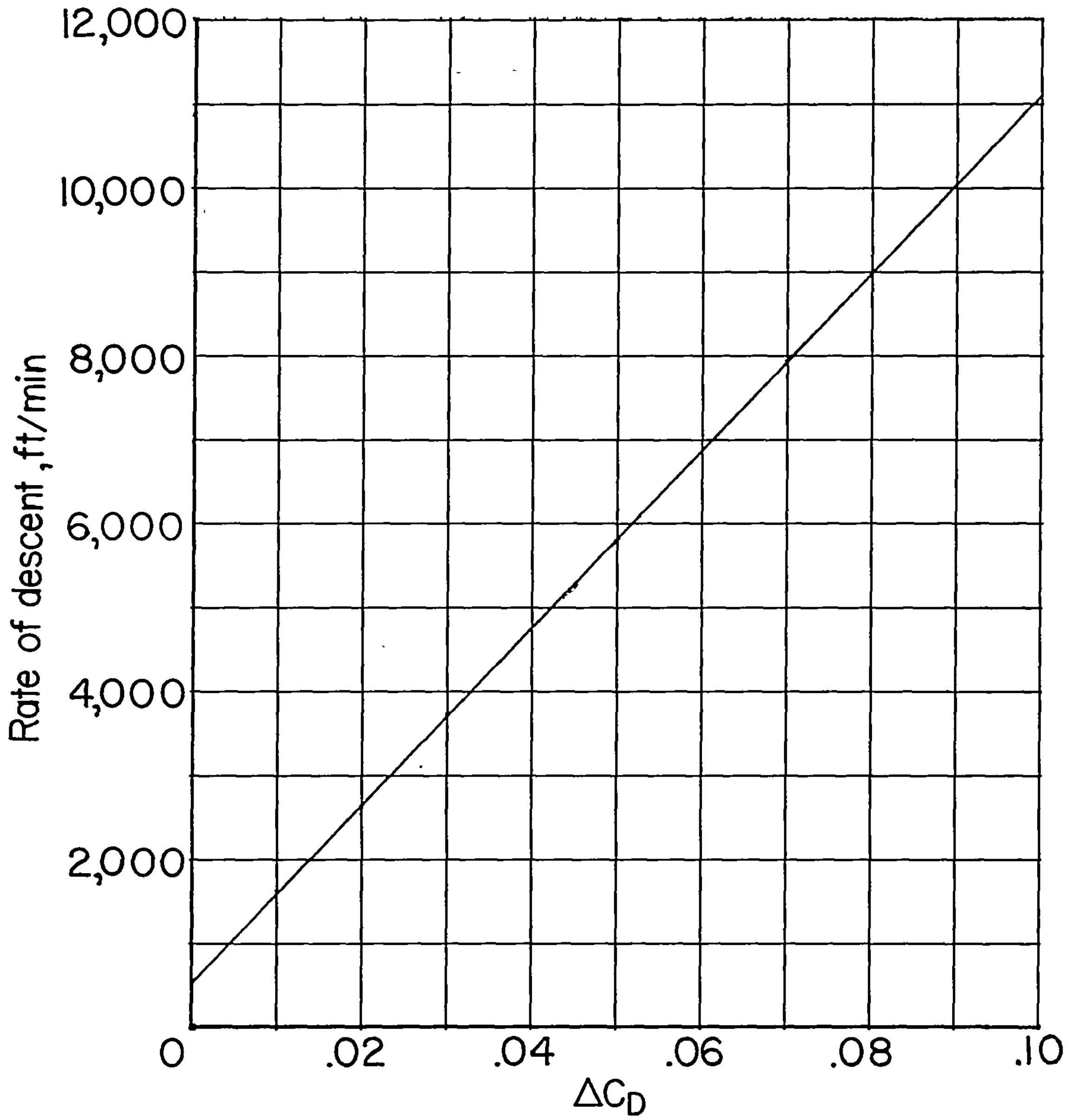

Figure 10.- Brake drag requirements for steady descent at V_{rough}. Jet transport; altitude, 30,000 feet; descent weight; engines idling.

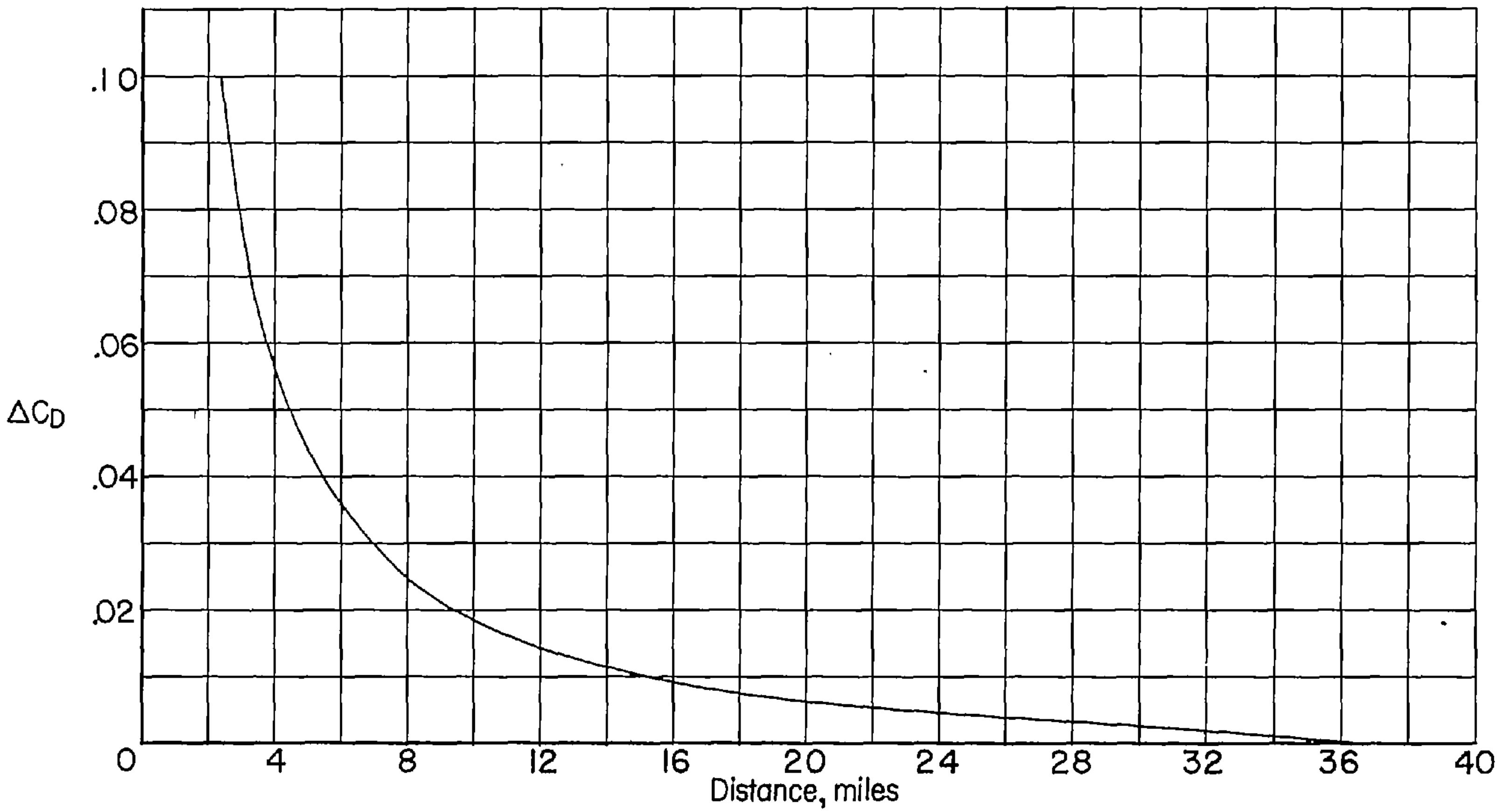

Figure 11.- Effect of drag brakes on deceleration distance. Jet transport; descent weight; altitude, 30,000 feet; engines idling; level flight.

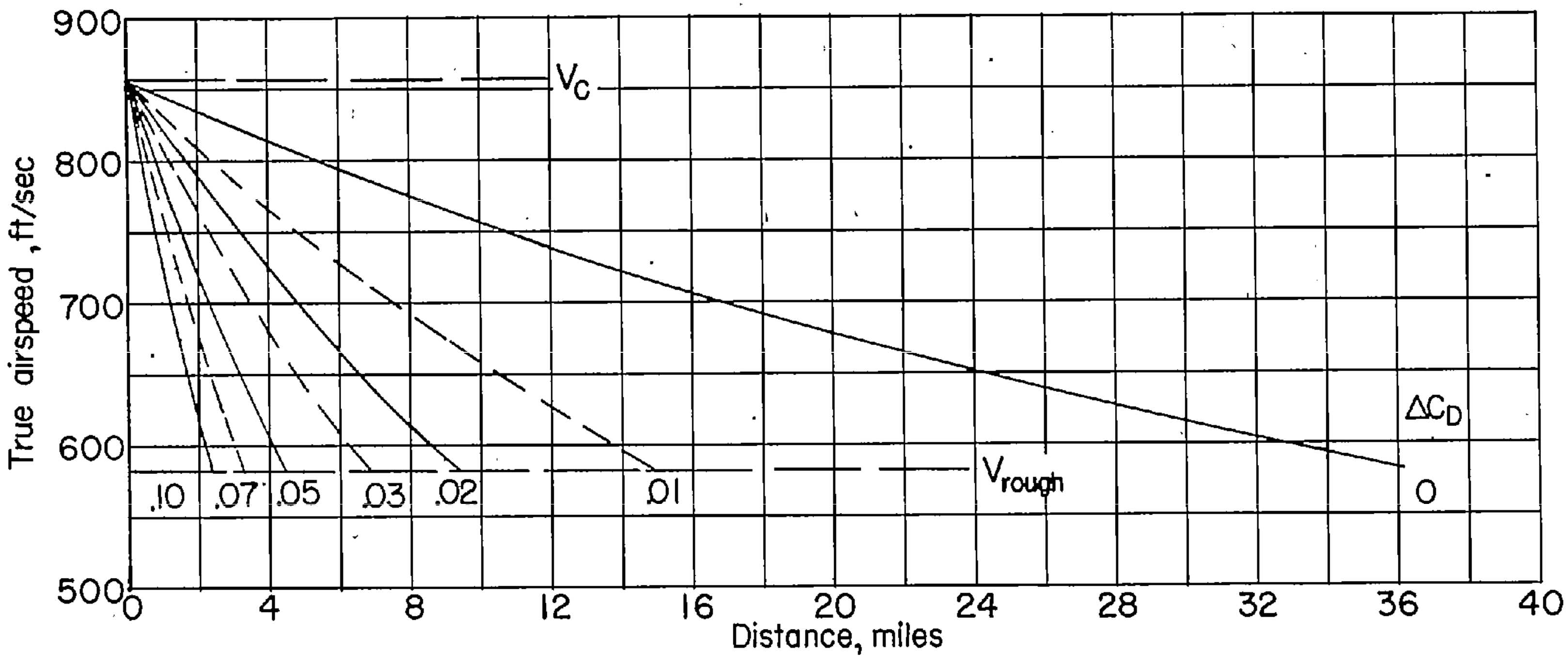

Figure 12.- Variation of true airspeed with distance for various values of ΔC_D. Jet transport; descent weight; altitude, 30,000 feet; engines idling; level flight.

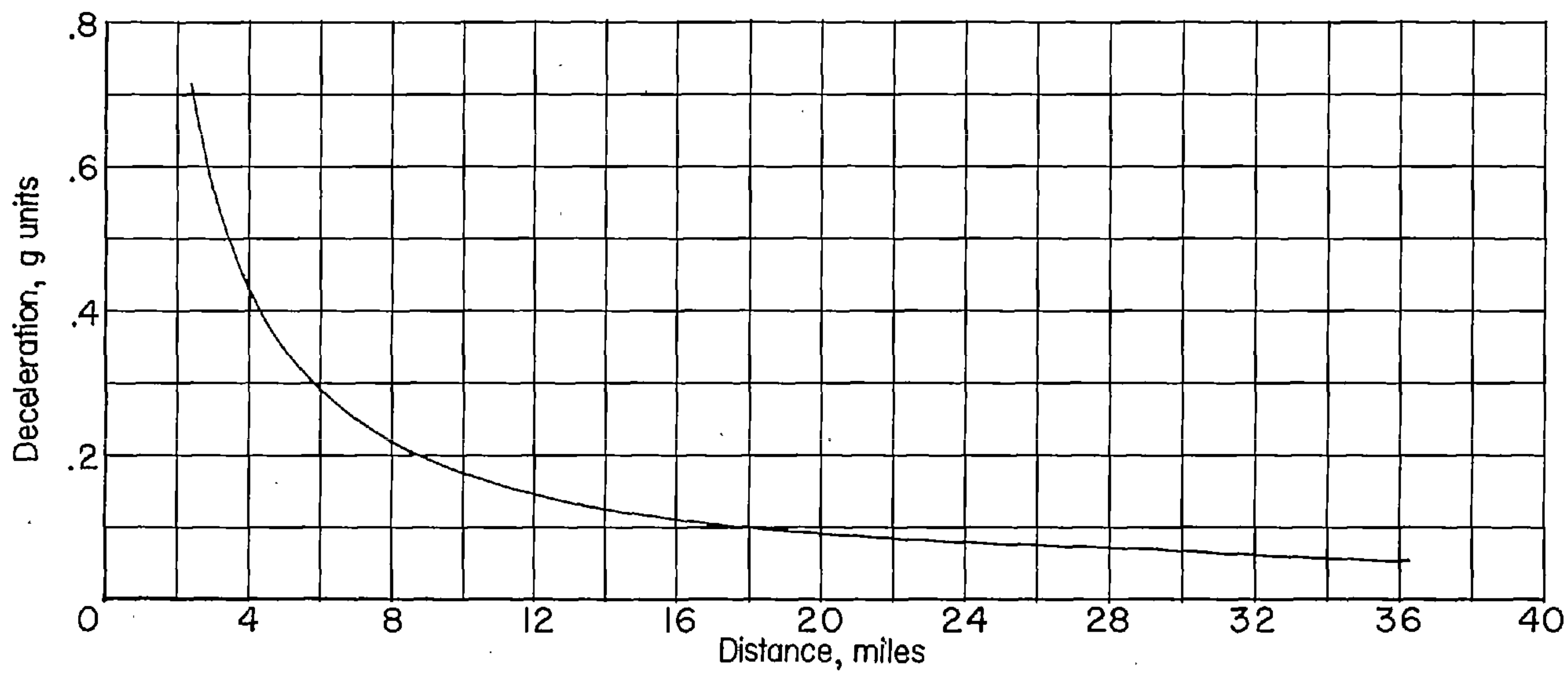

Figure 13.- Initial deceleration due to extending drag brakes and closing throttle as a function of deceleration distance. Jet transport; descent weight; altitude, 30,000 feet; level flight.

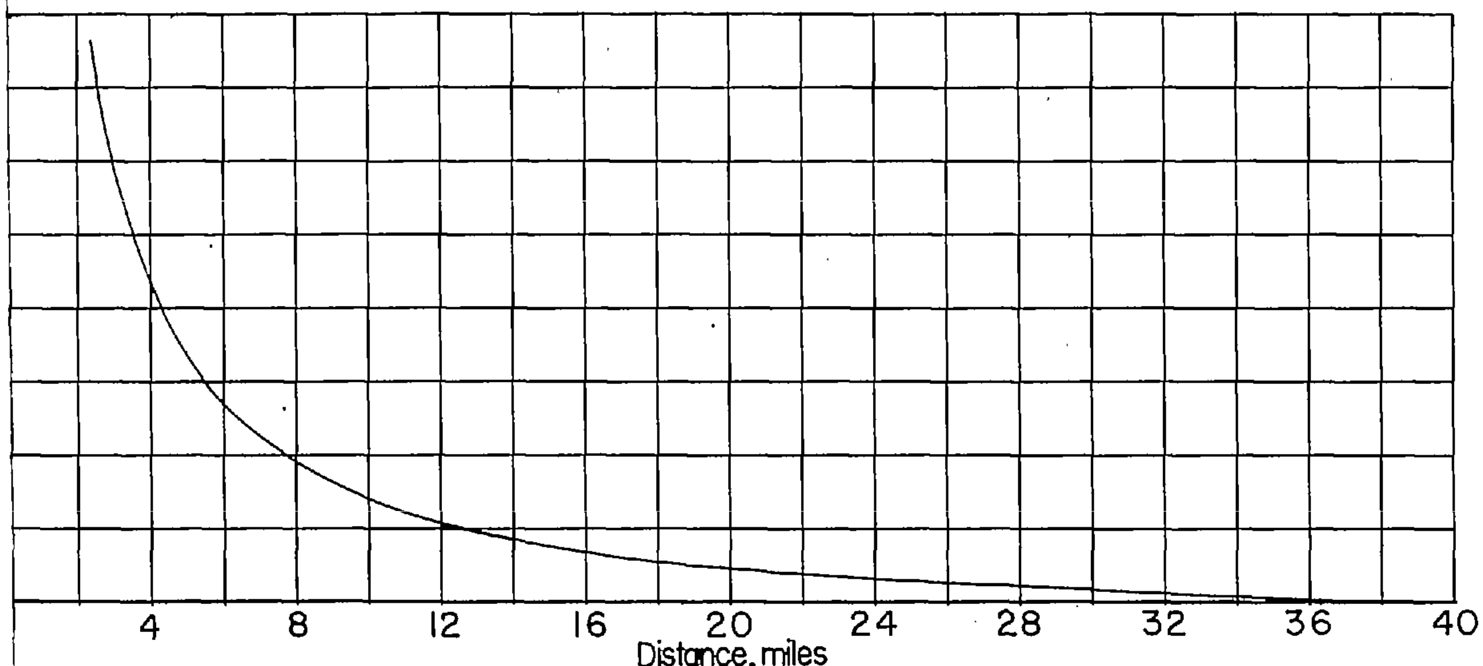

Figure 14.- Ratio of initial brake drag to thrust required for level flight at V_C as a function of deceleration distance. Jet transport; descent weight; altitude, 30,000 feet; engines idling.